# ECONOMICS AND PERFORMANCE OF PV HYBRID POWER SYSTEMS: THREE CASE STUDIES

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ABSTRACT

The Photovoltaic Systems Assistance Center (PVSAC) of Sandia National Laboratories (SNL) has been supporting the development and implementation of off-grid PV hybrid power systems for many years. Technical support has included:

- refining hardware
- understanding system design techniques
- obtaining operation and maintenance data
- studying use of energy produced

As part of the program, the PVSAC has provided technical expertise on hybrid systems to many federal agencies including the National Park Service, the Forest Service, the Bureau of Land Management, and the Department of Defense. The goal of these partnerships has been to ensure that reliable and safe PV hybrid systems are specified and procured. At present, a critical review of performance and cost of several representative PV hybrid systems is underway.

This paper presents a summary of the performance and economical analyses conducted on three PV hybrid systems.

## 1. THREE PV HYBRID POWER SYSTEMS

Three PV hybrid systems were selected for review because they represent three distinct types of remote electrical loads: large mini-grid or village power systems; single residential or commercial sites; and telecommunications repeaters.

The three PV hybrids selected for analysis were: 1) the large power system (115 kW of PV) at Dangling Rope Marina, UT.; 2) the small power system (9.6 kW of PV) at the Chaparral visitor area in Pinnacles National Monument, CA.; and 3) the telecommunications site at Rogers Peak, CA., which has 7.4 kW and 5.4 kW PV arrays. The performance of each hybrid system was documented and the 20-year life cycle cost (LCC) was calculated. This information is summarized in this paper. More details may be obtained from the authors.

### 1.1 Dangling Rope Marina

The National Park Service has operated a large photovoltaic (PV) hybrid power system at the Dangling Rope Marina since August 1996.

Key findings from the first year of operation are:

- Hybrid system availability was high (99.6%).
- Risk of a diesel fuel spill to Glen Canyon National Recreation Area and Lake Powell was eliminated.
- Annual fuel use was reduced from 62,123 gallons (diesel) to 54,442 gallons (propane).[1]
- Levelized cost of operating the hybrid (fuel, maintenance, and replacement costs) are $77k less per annum than for a diesel-only system.
- The 1996/97 site electrical load was 22% greater than anticipated in the system design analysis performed in 1992.

[1] Fuel savings are greater than the numbers indicate. By volume, propane contains only 2/3 the heat energy of diesel. Thus, the propane consumed is equivalent to about 36,000 gallons of diesel - energy savings of 42% compared to 1991 levels.

- The large site load resulted in greater fuel use and operating costs than anticipated by the 1992 analysis.

The original power system at Dangling Rope consisted of three diesel generators: two Caterpillar 310-kW prime power generators; and one Cummins 230-kW backup generator. This was replaced by the PV hybrid system which consists of a PV array, a battery bank, an inverter/rectifier, and two propane-fueled generators. The PV array consists of 384 ASE 300-DG/50 modules. The nominal array dc rating is 115 kW. The battery consists of 792 C&D model 6-C125-25 cells arranged in 40 steel trays. The bank is configured into four parallel strings with a total capacity of 2.4 MWh at the nominal 396 Vdc operating voltage. Array size and battery capacity were chosen after simulations by Sandia National Laboratories indicated favorable economics for this configuration.

The inverter/rectifier was built by Kenetech Windpower (now Trace Technologies). It uses the model HY-250 Power Processing Unit. In the inverting mode, it is rated at 250 kVA. Inverter size was selected to meet the peak site load (measured at 125 kW ac) while also charging batteries. The 250 kVA size also accommodates moderate future load growth. In addition to the PV power source, there are two Caterpillar model 3408 propane-fueled generators. Each is rated at 250 kVA, 3-phase, 480 Vac. The generators were sized to support worst-case block-loading conditions which could occur during inverter failure or black-out.

In addition to the subsystems mentioned, the entire hybrid system is monitored by a data acquisition system (DAS) designed and installed by the Southwest Technology Development Institute. The DAS monitors and records system performance and weather data. It can also exercise supervisory and control functions.

The loads at Dangling Rope are divided between the park and concessionaire residences and the concession store and fuel dock. When the hybrid was installed, steps were taken to reduce the overall electrical load. Compact fluorescent lamps replaced existing incandescent lamps in the residences. Also, several existing electrical appliances were replaced with propane-fueled units. These included 6 furnaces, 12 stoves, 12 water heaters, and 2 clothes dryers.

Figure 1 presents the monthly totals for the site electrical load and the energy produced by the generators and PV. Over the year, the site electrical load was 438.3 MWh. The ratio of largest to smallest monthly loads was about 2:1 with the largest loads occurring during mid-summer months and the smallest loads during the late-winter months. Overall, the two generators produced 345.4 MWh of electricity and the PV array produced 180.5 MWh (dc).

Thus, of the total generation on-site of 525.9 MWh, more than one-third was produced by the PV array. Since site load accounted for 438.3 MWh, system energy losses were 87.6 MWh, or 16.6% of all generation.

Approximately 58,808 gallons of fuel were delivered to the site during the year, of which 54,442 gallons were used by the generators. The balance was used by propane space heaters, stoves, and other appliances. Generator electrical production averaged 6.3 kWh/gal of propane consumed. Total generator run-time (split between two generators) was 2516 hours.

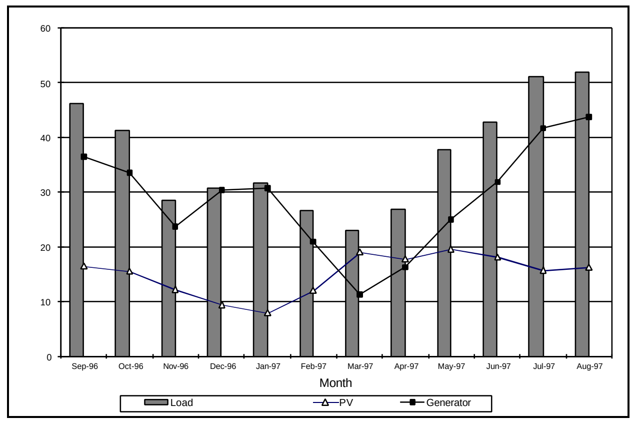


Figure 1. Monthly Electrical Load and Generation

The PV hybrid power system at Dangling Rope Marina has been in service for over one year. In that time, this complex system has had few serious problems and demonstrated excellent availability. Site operators report satisfaction with the overall system performance and power quality.

The few major problems experienced during the year were distributed between three major subsystems: inverter, generators, and battery. Overall, the system experienced 36 hours of downtime and was available for 99.6% of the time. Downtime records were not kept for the years prior to 1996. Interviews with long-time employees of the Marina's concessionaire indicate that reliability of power service has markedly improved since the hybrid system was installed.

The 1996/97 site electrical load was 438 MWh—larger than the 360 MWh load anticipated in 1992. Without implementation of an energy conservation incentive program for the site's concessionaire, site load will remain high.  Average cost of propane was $1.38 per gallon delivered by barge to the site.

Based on 1996/97 data, the net present value for 20-year operation of the PV hybrid is $2.89M.  This compares with $2.71M for a diesel generator power system, and $2.98M for propane generator system.  Thus, the hybrid is more expensive than full-time diesel generation and less expensive than full-time propane generation.  Compared with a propane generator system, the hybrid achieves payback (i.e. becomes less expensive) in year 19 of operation.

In summary: though not the economic windfall anticipated in 1992, the system has been reliable and efficient. Compared with a full-time generator alternative, it requires half the fuel and barge deliveries, produces less emissions, is quieter, and requires less regular maintenance.

1.2  Pinnacles National Monument

The performance of the 9.6 kWp PV hybrid power system installed by the National Park Service (NPS) at Pinnacles National Monument, CA., has been analyzed. NPS motivation for installation of this hybrid was not based on economics, but rather the need to replace two aging diesel gensets with an alternative that would be quieter, fuel efficient, and more in keeping with new NPS emphasis on sustainable design and operations. In January 1995, SNL and NPS staff assessed the Chaparral area at Pinnacles National Monument as a candidate for genset replacement with a renewable energy hybrid system.  The area included a maintenance shop, two residence trailers, a ranger station, a campground with comfort station, and parking area.  At the time, the site was served by two diesel gensets that needed to be replaced.  Gensets ran 24 hours per day. Review of 18 months of electrical meter readings showed an average site load of approximately 81 kWh per day.

Key to the favorable economic projections for this PV hybrid system was an integrated program of load management and load segmentation.  The net effect of this program was to reduce the original site loads by 50% and to divide them between two single-phase circuits, thus allowing the use of less-costly, off-the-shelf components. In this way, load segmentation kept initial costs down while load management ensured that, over time, the PV array would provide the large fraction of total site energy for which it was designed.

The analysis projects a net savings by the PV hybrid system of $83,561 and over 162,000 gallons of propane when compared with the genset-only system.  This net savings is independent of the costs associated with environmental emissions.

In late 1996, a PV hybrid power system was installed at the Chaparral area at Pinnacles.  The system comprised: 9.6 kW PV array (160 Solarex MSX-60 modules); 4200 Amperehour battery (12 model 6-75RC33 Resource Commander batteries); battery charge controller (Ananda Power model APT-4444-48); 24 kW inverter bank (six 4-kW Trace SW4048 120/240 inverters, configured as 4 in parallel serving one line and 2 in parallel serving the other); 20 kW generator (Kohler 20RZ, 20 kW generator configured for propane).  A data acquisition system (DAS) was installed on the PV hybrid to record the following parameters: PV, battery, load, and generator energy; battery string currents; battery voltage; battery, PV, and ambient temperatures; and irradiance.  Data have been taken from January 1997 to the present.

1.2.1  1997 Load, Energy Generation, and Fuel Use

Figure 2 presents the monthly energy fraction (in percent) produced by the genset and the PV array along with the monthly electrical load in kWh at Pinnacles.

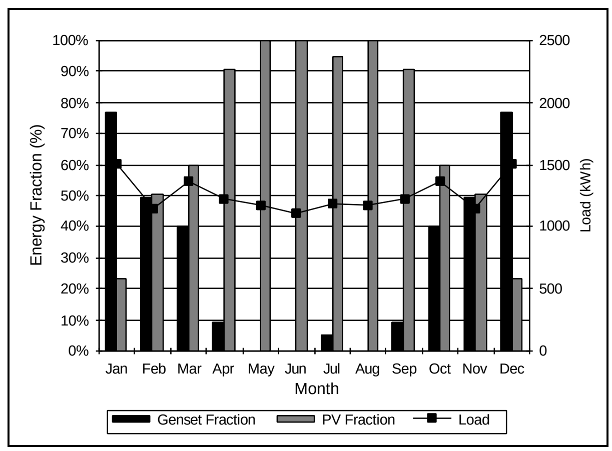


Figure 2.   Monthly Genset and PV Energy Fractions

From May through September, the array provided virtually all of the energy needed by the site.  Though site load is slightly higher in winter (due to increased lighting load and water pumping by comfort station pumps of winter rain runoff), it remains relatively constant throughout the year, varying from only 38 kWh/day in June to 47 kWh/day in January.  Noteworthy in the figure is that the program to reduce the site loads has been markedly effective: site load average has dropped from its original 81 kWh/day in 1995 to 41 kWh/day in 1997.

Figure 3 shows the monthly propane used by the PV hybrid system compared with the projected propane consumption that would be required to meet the site loads with genset-only operation. Estimated fuel consumption is based on measured site load and the genset manufacturer's published fuel consumption/load curve data.

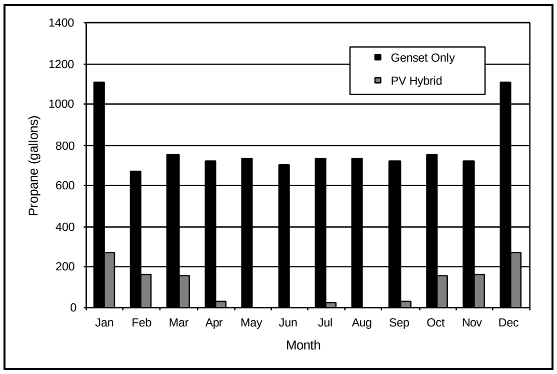


Figure 3. Fuel Use Comparison: Genset vs. PV Hybrid

Over the year, the PV hybrid genset runs only 793 hours and burns 1265 gallons of propane, a savings of 8146 gallons of propane over the genset-only system.

Of all PV hybrid systems evaluated through the DOE Photovoltaics Program, the Pinnacles National Monument system is the first to meet all expectations of environmental improvement, high reliability, and cost-effectiveness.

## 1.3 Rogers Peak

A PV hybrid power system replaced diesel generators on Rogers Peak in Death Valley National Monument, CA., in summer 1995. The power system is owned by Southern California Edison (SCE) and provides energy to telecommunications equipment serving SCE, California Department of Transportation, the National Park Service, the California State Police and emergency services, and cellular telephone providers.

The decision to use a PV hybrid system was based on two criteria: 1) the mountain top is remote and inaccessible by road during winter months, which makes fuel delivery and maintenance difficult; 2) over time, diesel fuel had spilled around the base of the generator and fuel tank. Such spills are environmental hazards and are expensive to remediate. The system at Rogers Peak, in the Death Valley National Monument, was specified in keeping with the National Park Service emphasis on wide-scale replacement of diesel generators by either propane-fueled generators or hybrid power systems that incorporate propane-fueled generators.

Construction of the PV hybrid power system at Rogers Peak began in Spring of 1995. It was completed in June of that year. The hybrid is actually two subsystems, each consisting of a PV array, battery bank, rectifiers, dc power center, and charge controllers. One propane-fueled generator provides all backup power for battery charging and for ac equipment loads.

The PV array for subsystem 1 is wired for 24 Vdc operation and consists of 62 Solarex MSX-120 modules with a nominal rating of 7.44 kWdc at standard test conditions (STC) of 1000 W/m$^2$ irradiance and 25°C module temperature. The array of subsystem 2 ( originally configured for 12 Vdc operation) was rewired in October 1996 for 24 Vdc operation. It consists of 45 Solarex MSX-120 modules with a nominal rating of 5.4 kWdc (STC).

Between both subsystems, there are 36 GNB Absolyte 1-100A-87 sealed, valve regulated lead acid (VRLA) batteries. The subsystem 1 battery, wired for a nominal 24 Vdc operating voltage, consists of 24 cells in two parallel strings with a total capacity of 10,800 Ahr (100 hour rate). The subsystem 2 battery has 12 cells with a capacity of 5,400 Ahr (100 hour rate) at a nominal 24 Vdc operating voltage. The battery charge controllers were designed by Applied Power Corporation.

The generator is a propane-fueled Onan Model 35EK-L unit generating 120/240 single-phase 35 kWac. In normal operation, the site uses only dc energy. The generator starts if voltage of either subsystem battery falls below preset levels. When service personnel are on-site, the generator is manually started to provide lights and ac equipment power—the most common use of the generator and accounts for almost all of the generator runtime.

In addition to the subsystems mentioned, the entire hybrid system is monitored by a dedicated data acquisition system (DAS) designed and installed by the Southwest Technology Development Institute. The DAS monitors and records system performance and weather data.

### 1.3.1 Energy Production and Site Load Data

The load on subsystem 1 has remained unchanged since monitoring began in 1995. Figure 4 shows the monthly PV and generator energy production for subsystem 1 along with the load for the 12 months of 1997. On average, the radio equipment on this circuit uses about 30.2 kWh of energy per day, equivalent to a continuous load of approximately 1.26 kWdc. As shown in the figure, the load is constant from month to month throughout the year.

The original 12 Vdc load for subsystem 2 was small. Prior to the upgrade of this circuit, the load averaged 1.6 kWh per day, equivalent to less than a 100 Wdc continuous load. The upgrade to 24 Vdc operation included the installation of the cell phone transceiver; the load increased four-fold. Figure 5 shows the monthly PV and generator energy production and the load for subsystem 2 for the 12 months of 1997 (after system upgrade to 24 Vdc operation). The average energy requirement is approximately 10.5 kWh per day, equivalent to a 440 Wdc continuous load. The load is almost constant from month to month.

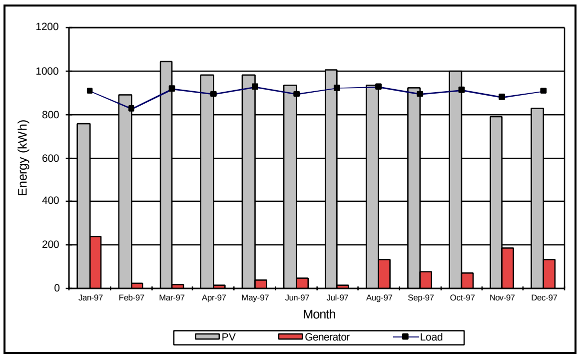


Figure 4. 1997 Rogers Peak Subsystem 1, PV Array and Generator Production, and Load.

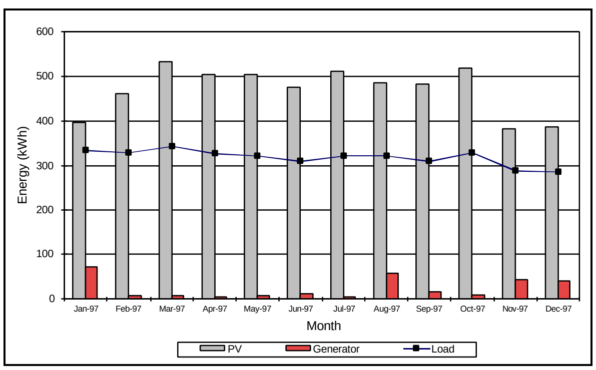


Figure 5. 1997 Rogers Peak Subsystem 2, PV Array and Generator Production, and Load.

### 1.3.2 PV Array Utilization

Both subsystem arrays were sized to allow growth of the on-site loads with time, and they can presently generate more energy than the site is using or can accept.

In 1997, the load and battery of subsystem 1 accepted 11,050 kWh of energy from the PV array. Based on modeling, this array was capable of producing about 15,700 kWh in the same period. These data indicate array utilization of 70% of the available PV energy. In the same period, subsystem 2 array utilization was only about 50% of the available energy. Subsystem 2 used 5,644 kWh of the 11,394 kWh available from the array. The array for subsystem 2 was intentionally oversized to ensure maximum reliability of the batteries powering the important police and emergency services radios on this circuit.

A lower system cost could have been obtained had oversizing of the arrays not been specified. Subsystem 1 requires only 44 of the installed 62 modules to meet the load. For subsystem 2, only 23 of the installed 45 modules are needed. In other words, 67 modules are required to meet the loads now served by 107 modules. Eliminating 40 120W modules at an estimated cost of $10/W would have reduced the initial installation cost by $48,000, from $287k to $239k and the payback from 13 to approximately 11 years.

During the first two and one-half years of hybrid system operation at Rogers Peak, the system availability has been virtually 100%. The risk of a diesel fuel spill at this remote mountain top within the Death Valley National Monument has been eliminated. The on-site generator ran just 250 hours and required only 515 gallons of propane in calendar year 1997. All factors show the PV hybrid power system on Rogers Peak has been a reliable source of energy for this telecommunications site. The hybrid has experienced no significant downtime in more than 2 years of operation. Overall, the PV has produced 93% of all required site energy. The propane-fueled generator produced the remaining 7%.

## 3. ECONOMIC

A summary of the economic analysis of each system is presented in this section. The economics of these three PV hybrid systems show that, compared with a generator-only power system, each hybrid has a much larger initial cost, followed by reduced fuel, maintenance, and capital replacement costs for the life of the system. The economic analyses shows that for all three sites, the PV hybrid can be a cost-effective option. Specific findings for the three systems are given below.

Dangling Rope—In broad terms, the hybrid saves over half the fuel and requires about one-third of the maintenance needed by either of the engine-only alternatives. Thus, annual fuel and maintenance costs and maintenance man-hours are far less. At the end of 20 years, the hybrid will have saved over one million gallons of propane that would have been required by the propane generator-only alternative. Dollar penalties for environmental emissions may be either included or excluded based on system purchaser, municipality or state regulations, or other conditions. The Dangling Rope Marina is in the Glen Canyon National Recreation Area, and National Park Service guidelines apply. These guidelines require that the following emissions costs be applied to energy projects within park facilities: $14/ton for $CO_2$; $0.75/lb for $SO_2$; $3.40/lb for $NO_x$.

The conversion of 36 existing electrical appliances to propane (fuel shifting), was a practical idea that will pay for itself in the first few years of operation. Propane-fueled water heaters, space heaters, and dryers capture between 50% and 80% of the fuel's heat energy for useful work. In contrast, the generators converted propane at a rate of approximately 6.3 kWh/gallon. While this is efficient operation for a generator, it represents only 23% conversion efficiency of the fuel's heat energy to electricity.

Pinnacles—The NPS was faced with replacement of the old diesel gensets. Therefore, for this economic analysis, the base case determines the costs associated with replacement of the two diesel gensets by two new 20-kW propane gensets The alternative case assesses the 20-year LCC of the PV hybrid system actually installed. The LCC analysis uses the DOE/FEMP 1996 recommended discount rate for federal energy conservation projects of 4.1%. The LCC estimate projects a net savings associated with the PV hybrid of $83,561 over the 20-year service life. This equates to a simple payback period of 7 years and a discounted payback period of about 11 years. In addition, the PV hybrid will save over 8,000 gallons of propane fuel each year, or over 162,000 gallons during a 20-year service life.

Rogers Peak—Though 5 times more expensive to purchase than a genset-only system, the 20-year life cycle cost (LCC) for the PV hybrid is actually less, with a discounted payback of about 11 years. In addition, over its 20-year life, the PV hybrid will consume 162,000 fewer gallons of propane and avoid the emissions of over 1,000 tons of $CO_2$ and 1.5 tons of $NO_x$ compared with the genset-only system. Thus, using National Park Service emissions costs guidelines, the PV hybrid also saves an additional $939 per year when compared with operation of a genset-only system. The cost effectiveness of this PV hybrid system is due to the combined effects of active load management, load segmentation, and effective system design.

A comparison of the results from the economic evaluations is provided in Figure 6. Of particular importance is the value of the recurring cost as a fraction of the overall net present value (NPV). While recurring maintenance costs are limited to about 5%, the overall recurring costs (maintenance plus capital replacement) run as high as ~25%.

| | DANGLING ROPE | | | PINNACLES | | ROGERS PEAK | |
|---|---|---|---|---|---|---|---|
| Costs | Diesel Only | Prop Only | Hybrid | Prop Only | Hybrid | Prop Only | Hybrid |
| Init. Cap. | 87 | 87 | 1,300 | 24 | 135 | 24 | 287 |
| Rec. Maint | 394 | 394 | 190 | 74 | 10 | 195 | 10 |
| Fuel | 2,067 | 2,337 | 1,198 | 165 | 22 | 144 | 8 |
| Cap Repl. | 164 | 164 | 201 | 32 | 44 | 45 | 47 |
| NPV | 2,711 | 2,981 | 2,890 | 295 | 211 | 408 | 352 |

Figure 6. 20 Year Life-Cycle Cost Comparison (in thousands of dollars) of Three Hybrid Systems.

## 4. CONCLUSIONS

The PVSAC at SNL continues to work with parties interested in using renewable energy to meet some or all of their energy needs. The focus on larger PV hybrid systems will continue as there are many applications where these offer competitive options, particularly for federal agencies.

The studies of these three systems show that PV hybrid systems are a practical and economic alternative for many diversified applications. Incorporation of the PV array reduces generator fuel and maintenance costs and makes the power system more environmentally benign. As the records of these example systems indicate, the reliability is high and maintenance is lower than for genset-only alternatives. Although initial cost is typically higher than fueled generators, the life-cycle cost can be less expensive, particularly when costs of emissions are included.

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